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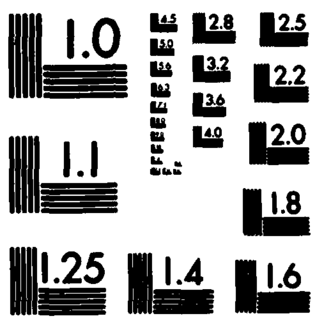

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This report reviews the program of work performed under Grant AFOSR-84-0042 during the period 1 January 1984 to 31 May 1985. The following topics were studied: generalization of a set of constitutive equations to include thermal dependence of viscoplastic flow and thermal recovery of hardening, determination of the effective thermo-elastic-viscoplastic properties of metal matrix composites including the influence of residual thermal stresses, and the generalization of the constitutive equations to the case of large deformations. Publications based on the research program are listed.

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THERMOMECHANICAL EFFECTS IN INELASTIC MATERIALS AND STRUCTURES

Sol R. Bodner
Material Mechanics Laboratory
Faculty of Mechanical Engineering
Technion - Israel Institute of Technology
Haifa 32000, Israel

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Thermomechanical Effects in Inelastic Materials and Structures

by

Sol R. Bodner*
Principal Investigator

Abstract

This report reviews the program of work performed under Grant AFOSR-84-0042 during the period 1 January 1984 to 31 May 1985. The following topics were studied: generalization of a set of constitutive equations to include thermal dependence of viscoplastic flow and thermal recovery of hardening, determination of the effective thermo-elastic-viscoplastic properties of metal matrix composites including the influence of residual thermal stresses, and the generalization of the constitutive equations to the case of large deformations. Publications based on the research program are listed.

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* Professor, Faculty of Mechanical Engineering
Technion - Israel Institute of Technology, Haifa 32000, Israel

Objectives and Achievements

The overall objective of this phase of the research program was to examine the effects of temperature on the time dependent inelastic response of materials. A set of constitutive equations for elastic-viscoplastic material behavior was taken as the basis of the investigation. These equations do not require a yield criterion or loading and unloading conditions and are motivated by physical considerations. The constitutive equations were generalized to include temperature dependence of inelastic flow and thermal recovery of hardening. In principle, these equations can be applied as the material representation in structural problems involving time dependent histories of temperature and force loading.

A review paper on the complete set of constitutive equations including temperature effects was prepared as part of the current research program and is listed as no.1 in the list of publications. This paper will appear as a chapter in a book dealing with "unified" constitutive equations.

One of the interesting and important applications of the elastic-viscoplastic constitutive equations with consideration of thermal effects is to metal matrix composites. In fact, a major part of the effort in this research program was directed towards examining thermal effects in metal matrix composites leading to six publications on this subject. Thermal considerations enter in a number of ways including the basic fabrication operations. Since these materials are usually consolidated at an elevated temperature, residual stresses arise due

to the composite composition when they are cooled to ordinary working temperature. Determination of these residual stresses and analysis of their influence on subsequent loading histories is one of the topics that has received particular attention.

As noted, six publications were prepared on thermal effects in elastic-viscoplastic metal matrix composites. In paper no.2 on the list of publications, the average behavior of the composite was determined from the given elastic, thermal and plastic properties of the individual constituents. In paper no.3, the question of the effect of residual stresses created by cooling the metal-matrix inelastic composite from its curing temperature to room temperature is investigated. In particular, conditions for the shakedown of the composite when it is subjected to mechanical loadings is discussed. Having established a method for determining the effective behavior of inelastic temperature dependent composites, it is possible to extend the investigation to laminated composites. In paper no.4, constitutive equations are presented for laminated inelastic composites. Each layer is temperature dependent elasto-plastic and given by the theory developed in paper no.2. In particular, the gross behavior of the laminated composites in stretching and bending is determined.

In papers no.5 and no.6, analytical methods for the determination of the effective mechanical and thermal properties of unidirectional and tri-orthogonally fiber-reinforced materials are given. In paper no.7, constitutive relations governing the

elastoplastic behavior of porous materials are given and implemented. Generalization to filled, long and short fiber composites is possible.

A topic that is currently of strong interest and which has generated some controversy in the Mechanics community is the proper development of a plasticity theory with large deformations that accounts for both isotropic and directional hardening. This subject is important not only for applications involving large strains but because of the implications on the capability of generalization of "small strain" constitutive equations. It was therefore considered desirable to devote some effort to extending the constitutive equations used as the reference in the current research program to the large deformation case. The exercise proved to be successful and a paper based on the work has been accepted for publication - no.8 on the publication list.

Personnel

In addition to the Principal Investigator, Professor S. R. Bodner, the following persons were engaged on the research program:

Professor Jacob Aboudi (Tel Aviv University)

Dr. Miles Rubin (Technion)

Both Professor Bodner and Professor Aboudi participated in the International Symposium on Plasticity which was held at the University of Oklahoma, Norman, Oklahoma, in July-August 1984. They presented lectures based on results obtained in the research program sponsored by AFOSR/EOARD.

Publications of Research Program

1. "Review of a Unified Elastic-Viscoplastic Theory", by S. R. Bodner, Interim Scientific Report on Grant AFOSR-84-0042, October 1984 to be published as a chapter in: "Unified Constitutive Equations for Plastic Deformation and Creep of Engineering Alloys", A. K. Miller (editor), Elsevier Applied Science Publications.

Abstract - A review is given of a set of constitutive equations for elastic-viscoplastic materials that do not require a yield criterion or loading and unloading conditions. In their present state of development, the equations can provide for certain important characteristics of strain rate dependent inelastic deformation namely: isotropic and directional hardening leading to cyclic stress-strain relations with cyclic hardening or softening, additional hardening due to nonproportional loading, thermal recovery of both isotropic and directional hardening, temperature and pressure dependence, and isotropic and directional damage development. The equations have been used to model a number of metals over a wide range of temperatures and strain rates and examples are presented. Applications of the equations to various engineering problems are described.

2. "The Effective Thermomechanical Behavior of Inelastic Fiber-Reinforced Materials", by J. Aboudi, International Journal of Engineering Science, in press.

Abstract - A continuum theory is presented for the prediction of the average behavior of unidirectional fiber-reinforced materials in which both constituents are thermoelastic in the linear region and thermo-inelastic in the nonlinear region. The resulting effective constitutive equations are given by a set of temperature dependent incremental relations from which the response of the composite to a given mechanical and thermal loading can be determined. The derived theory is applied to investigate the overall behavior of unidirectional graphite fibers reinforcing an aluminum alloy matrix under various types of applied stresses and temperature changes. In particular, the effect of residual stresses developed when the composite is cooled is investigated.

3. "Inelastic Behavior of Metal-Matrix Composites at Elevated Temperature", by J. Aboudi, International Journal of Plasticity, in press.

Abstract - A set of constitutive relations are given for the prediction of the overall behavior of fiber-reinforced materials, in which both matrix and fiber constituents are thermoelastic-thermoviscoplastic materials. The temperature-dependent response of the composite to a given loading is determined from the set of equations by an incremental procedure in time. The theory is applied to investigate the overall response of unidirectional graphite thermoelastic fibers reinforcing an elastic-thermoviscoplastic aluminum matrix to thermal and mechanical loadings. The residual microstresses and microstrains which develop in the composite when it is cooled from its curing temperature are investigated. The effect of this residual field on the overall behavior of the composite when it is subjected to various types of mechanical cyclic loadings is studied.

4. "Constitutive Relations for the Thermomechanical Behavior of Fiber-Reinforced Inelastic Laminates", by J. Aboudi, Journal of Composite Structures, in press.

Abstract - The thermomechanical behavior of laminated composites in which every lamina is unidirectional fiber-reinforced thermo-inelastic material is determined by a micromechanics analysis followed by a macromechanics one. In the micromechanics analysis, effective constitutive relations are derived for unidirectional fibrous materials in which the matrix and fiber phases are thermoelastic in the linear region and thermo-inelastic in the nonlinear region. The derivation is based solely on the material properties of fibers and matrix and amount of reinforcement. By a macromechanics analysis, the gross behavior of the laminated composite in stretching and bending deformation is determined. Applications are given for the deformation field developed in cooling and reheating of graphite/aluminum laminated plates.

5. "Effective Thermoelastic Constants of Short-Fiber Composites", by J. Aboudi, Fibre Science and Technology, Vol. 20, 1984, pp. 211-225.

Abstract - A unified method of analysis for the determination of the effective thermal expansion coefficients, specific heats, and thermal conductivities of unidirectional short-fiber composites is given. The overall thermal constants of long-fiber and particulate composites are obtained as special cases. In addition, the method provides the effective thermal coefficients of isotropic and quasi-isotropic composites with randomly oriented short fibers.

6. "Minimechanics of Tri-Orthogonally Fibre-Reinforced Composites: Overall Elastic and Thermal Properties", by J. Aboudi, Fibre Science and Technology, Vol. 21, 1984, pp. 277-293.

Abstract - A method is given for the prediction of the effective elastic moduli and coefficients of thermal expansion of composite materials reinforced in three orthogonal directions. The proposed approach is based on the minimechanics analysis of a repeated representative cell of the three-dimensionally oriented fibre composite. Illustrations are given for a carbon/carbon composite.

7. "Elastoplasticity Theory for Porous Materials", by J. Aboudi, Mechanics of Materials, Vol. 3, 1984, pp. 81-94.

Abstract - A continuum theory is derived for the modeling of elastoplastic work-hardening porous materials. The theory provides a set of constitutive relations which, using the properties of the inelastic matrix, determines by an incremental procedure the overall response of the porous solid to various types of loading. In the elastic region, effective elastic moduli of the porous material are obtained. Comparison with theoretical and experimental results are given.

8. "An Elastic-Viscoplastic Model for Large Deformation", by M. B. Rubin, International Journal of Engineering Science, in press.

Abstract - In this paper we have shown that the theory of an elastic-viscoplastic work hardening material proposed by Bodner and Partom (1975) and Bodner (1984) for small deformations may be generalized for large deformations by reformulating the equations using Lagrangian quantities. Restrictions on the general constitutive equations were obtained using the thermodynamic procedures proposed by Green and Naghdi (1977, 1978a). In this formulation, the stress is determined directly from deformation quantities and, in particular, is not calculated using a hypo-elastic type equation for a stress rate. Also, since Lagrangian quantities are used, there is no need to introduce special rates like the Jaumann rate in the evolution equations. Specific constitutive equations were proposed for a material exhibiting isotropic-elastic response in its reference configuration, strain-rate and temperature dependent plastic flow with isotropic and directional hardening, and thermal recovery of hardening. These specific equations use only the material constants obtained from the corresponding small deformation theory. Examples of simple tension and simple shear show that these equations predict physically plausible material response for large deformations.